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# Carbonation Behavior of Repeated Recycled Fine Aggregate Concrete under Bending Load

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## Abstract

Carbonation resistance is an important factor affecting the durability of concrete, and the carbonation behavior of structural concrete become more complex under loading. In order to investigate the feasibility of utilizing Recycled Fine Aggregate (RFA) in structural concrete under a coupling of bending load and carbonation, two generations of repeatedly Recycled Aggregate Concrete ($RAC_1$ and $RAC_2$) with four different replacements level (10%, 20%, 30%, and 40%) of Natural Fine Aggregate (NFA) by RFAs were prepared, and carbonation depths of all concrete mixes were tested under an action of bending load of 40, 70, 100, and 120% of failure load. The results indicated that the repeated RAC successfully reached the target slump and target compressive strength, despite both workability and compressive strength decreased with increasing RFA replacement ratio. The carbonation depth of repeated RAC increased with the increasing replacement ratio of RFA. With bending load increasing, the carbonation depth of repeated RAC also increased except for the specimens suffered 70% of failure load. The resultant insights demonstrate the feasibility of using repeated RAC to design a service lifetime of 50 years in practical engineering.

Keywords: *repeated recycled aggregate concrete, recycled fine aggregate, compressive strength, carbonation resistance, bending load*

## 1. Introduction

Concrete is the most widely used building material in the construction industry over the world and the extensive application of concrete has led lots of economic and environmental problems, including the ecological environment of natural aggregate was destroyed, and a mass of construction wastes were produced. According to the statistics, new buildings consumed 0.4–0.7 tons of sand per square meter, and there were about 4.9 billion tons of natural fine aggregates required annually in China. The shortage of natural sand resources has occurred in many areas of china, and has affected the course of the construction of urbanization. Thus, there is an urgent need to find substitutes for natural fine aggregates. At the same time, the amount of construction waste reached up to 2 billion tons during the process of building, demolition and reconstruction projects each year in China (Wang *et al.*, 2014), and only 5% of construction waste were recycled for reusing. Repeatedly recycling using abundant waste concrete as recycled aggregate for structural concrete can provide a double benefit by simultaneously compensating for the critical shortage of natural aggregates and reducing environmental stress (Deng *et al.*, 2017). Therefore, the interest in utilizing waste concrete as a replacement for natural aggregate in structural concrete is increasing (Xuan *et al.*, 2016).

Recycled Aggregate Concrete (RAC) satisfies the sustainable development of resources and environment; however, the recycled aggregate has the disadvantages (Silva *et al.*, 2014) of rough surface, high water absorption, large porosity and many internal micro-cracks, so the mechanical properties and durability of RAC must be considered during the practical application. In recent years, some scholars have focused on the application of recycled aggregates from waste concrete and corresponding concrete, and most findings support the feasibility of using RAC to produce structural concrete (Li *et al.*, 2016; Zhang *et al.*, 2017; Akbarnezhad *et al.*, 2011). However, far fewer studies have been conducted on Recycled Fine Aggregate (RFA). Khatib (2005) conducted experiments of RAC in which Natural Fine Aggregate (NFA) was replaced by RFA at 0%, 25%, 50%, 75%, and 100%, and the results demonstrated that the compressive strength was only reduced by 15%, when the replacement ratios were up to 75%. Fan (2016) tested the mechanical properties of different concrete prepared with two types of RFAs from crushing concrete wastes, which arrived at the conclusion that the crushing process and the RFA replacement ratio would significantly affect

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the quality of the resulting RAC, however, RFAs can be used as replacements for NFA in concrete. All these researches accounted that RFA used in mortar and concrete production is feasible, which does not severely jeopardize the mechanical properties of concrete (Corinaldesi *et al.*, 2009; Braga *et al.*, 2012).

Carbonation is one of the most important factors affecting the durability of concrete. In the south of China, the concrete structure are suffering from carbonized erosion due to the warm and humid climate, especially the wharf, cross-sea bridge and other existing concrete structures. Therefore, study on the carbonation resistance of RAC under loading environment plays an important role in promoting the application of RAC in practical engineering and alleviating the durability failure of concrete structure in coastal areas. The negative influence of RFA on the structural performance of RAC has been reported, particularly with respect to durable properties. Evangelista (2010) investigated the effect of 30% and 100% RFA replacement ratios on the carbonation resistance of RAC and found maximum increases of 40% and 100% of RAC carbonation depth compared with Natural fine Aggregate Concrete (NAC). Xingwei Liu (2009) performed an experimental study on the carbonation of RAC and reported that the carbonation resistance of RAC decreased with increasing replacement ratio of RFA. Li (2017) primarily concluded that the water cement/ratio played an important role in the carbonation resistance of RAC, which decreased with increasing water/cement ratio. Zega (2011) studied the carbonation resistance of RAC after 310 and 620d exposure tests and found that the carbonation depth of RAC under the lower water/cement ratio was similar to that of NAC. These studies suggested that RFA can be used in structural concrete when used to replace natural fine aggregate at a low ratio in the proper environment.

This study investigated the carbonation process of concrete beam under loading environment to evaluate the feasibility of the repeated use of RFA in structural concrete. Two different generations of repeated RFA concretes (symbolized by $RAC_1$, $RAC_2$) were prepared using corresponding recycled fine aggregates (symbolized by $RFA_1$, $RFA_2$) with four replacement ratios (10%, 20%, 30%, and 40%) to replace the NFA. Meanwhile, Natural fine Aggregate Concrete (NAC) was made as reference concrete. The compressive strength and carbonation depth of NAC, $RAC_1$ and $RAC_2$ under four bending load levels (40%, 70%, 100%, and 120% of the failure load) were measured and discussed. The findings from this study will promote the application of repeated RAC in practical engineering.

## 2. Experimental

### 2.1 Raw Materials

In this research, the natural river stone (size: 5−16 mm) and medium sand (fineness modulus: 3.02) were used as coarse and fine aggregates respectively for all concretes. The cement used was grade 42.5R ordinary Portland cement with an apparent density of 2,963 kg/m$^3$. Furthermore, fly ash with an apparent density of 2,500 kg/m$^3$, slag with an apparent density of 2,667 kg/m$^3$, and silica fume with an apparent density of 2,759 kg/m$^3$ were used as three different types of mineral admixture to enhance the workability and strength of the repeatedly recycled concrete. The detailed chemical compositions of the cement and mineral admixture are listed in Table 1. In addition, poly carboxylic acid was used as water reducing agent, and polypropylene fibre was used as reinforcing agent to improve the strength of the repeatedly recycled concrete.

### 2.2 Preparation of Two Generations of RFAs

This study mainly focuses on evaluating the feasibility of using the repeatedly recycled fine aggregate for structural concrete under loading environment. For this purpose, carbonation behaviour of natural fine aggregate concrete and two different generations of RAC containing repeatedly recycled fine aggregate subjected to bending load was investigated. Refer to the production process of recycled concrete aggregates studied by Zhu *et al.* (2016), the first-generation Recycled fine Aggregate Concrete ($RAC_1$) was prepared using 70% first-generation Recycled Fine Aggregate ($RFA_1$) with particle sizes of 0.15−4.75 mm to replace NFA, $RFA_1$ was obtained commercially from demolished concrete structural buildings with more than 50 years of service life. After a 28 d standard curing, the $RAC_1$ specimens were crushed, dried and screened to obtain the second-generation Recycled Fine Aggregate ($RFA_2$). Then, $RFA_2$ was sieved with the same particle sizes as $RFA_1$ to produce the second-generation Recycled fine Aggregate Concrete ($RAC_2$).

### 2.3 Mix Proportions

In this study, the target strength grade and target slump of the three types of concrete were designed as 30 MPa and 150 mm, respectively. Two generations of Recycled fine Aggregate Concrete ($RAC_1$, $RAC_2$) were prepared using $RFA_1$ and $RFA_2$ to replace NFA at four different replacement ratios (10%, 20%, 30% and 40%). The mix proportions were calculated according to JGJ55-2011 (2011), and the details of all mix proportions are listed in Table 2.

Table 1. Chemical Composition of the Cementitious Materials

| Component (%) | CaO | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | MgO | MnO | $K_2O$ | $TiO_2$ | $SO_3$ | Others |
|---|---|---|---|---|---|---|---|---|---|---|
| Cement | 60.81 | 21.31 | 7.32 | 3.84 | 1.16 | 0.15 | 0.63 | 0.24 | 2.06 | 2.40 |
| Slag | 26.45 | 32.36 | 17.01 | 1.32 | 7.87 | 0.46 | 0.96 | 0.87 | 0.72 | 0.70 |
| Fly ash | 3.82 | 52.48 | 28.31 | 3.68 | 1.13 | 0.21 | 1.69 | 0.98 | 1.75 | 5.96 |
| Silica fume | 0.23 | 86.18 | 1.08 | 0.92 | 0.78 | 0.13 | - | - | 0.84 | 2.63 |

Table 2. Mix Proportions of NAC and Repeated RAC

| Material (kg/m³) | NAC | RAC | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Replacement ratio (%) | | | | | | | |
| | | 10 | | 20 | | 30 | | 40 | |
| | | $RAC_1$ | $RAC_2$ | $RAC_1$ | $RAC_2$ | $RAC_1$ | $RAC_2$ | $RAC_1$ | $RAC_2$ |
| Gravel | 1185 | 1105 | 1044 | 1099 | 1023 | 1033 | 1021 | 1024 | 1009 |
| NFA | 586 | 543 | 522 | 469 | 459 | 425 | 397 | 374 | 336 |
| RFA | 0 | 73 | 58 | 120 | 115 | 178 | 170 | 230 | 225 |
| Cement | 207 | 207 | 207 | 207 | 207 | 207 | 207 | 207 | 207 |
| Fly ash | 184 | 184 | 184 | 184 | 184 | 184 | 184 | 184 | 184 |
| Silica fume | 23 | 23 | 23 | 23 | 23 | 23 | 23 | 23 | 23 |
| Slag | 46 | 46 | 46 | 46 | 46 | 46 | 46 | 46 | 46 |
| Water reducer | 2.25 | 2.25 | 2.25 | 2.25 | 2.25 | 2.25 | 2.25 | 2.25 | 2.25 |
| Fibre | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 |
| Water | 189 | 190 | 194 | 197 | 199 | 201 | 204 | 205 | 209 |

### 2.4 Specimen Production and Test Methods

Concrete specimens with a size of 100 mm × 100 mm × 400 mm were used. Firstly, the specimens were loaded under four bending stress levels (40%, 70%, 100% and 120% of the failure load) in special loading equipment composed of high-performance concrete as designed by Jin *et al.* (2005). As a whole, the loading equipment and specimens were then put in the rapid carbonation box ($CO_2$ concentration of 20%, relative humidity of 70%, and temperature of 20°C) lasting 7 d, 14 d, 21 d, and 28 d. Finally, the carbonation depth of the specimens was measured by spraying phenolphthalein reagent on the fracture surface according to GB/T 50082-2009 (2009).

## 3. Test Results

### 3.1 Physical Properties of the Fine Aggregates

The physical properties of NFA, $RFA_1$ and $RFA_2$ are shown in Table 3. It could be seen in Table 3 that the quality of the fine aggregates declined with increasing repeated times of RFA. Compared to NFA, the water absorption of repeated RAC increased sharply, the apparent density of $RFA_1$ and $RFA_2$ decreased by 8.9% and 10.9%, and the fineness modulus increased by 0.1 and 0.3. Compared to recycled mortar incorporating $RFA_1$, the water demand ratio of recycled mortar incorporating $RFA_2$ increased by 2%, and the compressive strength ratio only decreased by 0.05%. The main reasons for the decline of physical properties are that mortar absorption occurred increasingly on the surface of the recycled fine aggregates and the hydration speed of $C_2S$ decreased with the increase in cycling times (Mu *et al.*, 2014). Meanwhile, the high porosity inside the recycled fine aggregates affected the physical properties of the repeated RFA. It should be noted that the physical property results in Table 3 declared that all of the indices tested meet the requirements of recycled fine aggregate for concrete and mortar. $RFA_1$ and $RFA_2$ belong to Class II and Class III according to GB/T 25176-2010, respectively, and both of them fall into Class L in terms of JIS A5308-2009 (2009).

### 3.2 Workability and Compressive Strength of the NAC and RAC

The slump values of the different concretes are listed in Table 4. It could be observed that the slump values of NAC and two generations of RAC with different replacement ratios (10%, 20%, 30% and 40%) all achieved the target slump of 150 mm,

Table 3. Physical Properties of the Fine Aggregates

| Type | Apparent density (kg/m³) | Water absorption at 24 h (%) | Water demand ratio of recycled mortar (%) | Compressive strength ratio of recycled mortar (%) | Fineness modulus |
|---|---|---|---|---|---|
| NFA | 2616 | 1.2 | - | - | 2.7 |
| $RFA_1$ | 2382 | 12.1 | 1.31 | 0.93 | 2.8 |
| $RFA_2$ | 2329 | 13.0 | 1.51 | 0.88 | 3.0 |

Table 4. Slump and Compressive Strength of the NAC and RAC

| Replacement ratio/% | | NAC | 10 | | 20 | | 30 | | 40 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Concrete type | | | $RAC_1$ | $RAC_2$ | $RAC_1$ | $RAC_2$ | $RAC_1$ | $RAC_2$ | $RAC_1$ | $RAC_2$ |
| Slump (mm) | | 188 | 175 | 169 | 170 | 165 | 167 | 162 | 160 | 157 |
| Compressive strength (MPa) | 28d | 42.8 | 41.8 | 39.8 | 41.3 | 39.6 | 38.7 | 36.8 | 37.1 | 35.6 |
| | 90d | 49.6 | 49.1 | 47.5 | 49.0 | 47.2 | 47.8 | 44.9 | 46.3 | 42.2 |

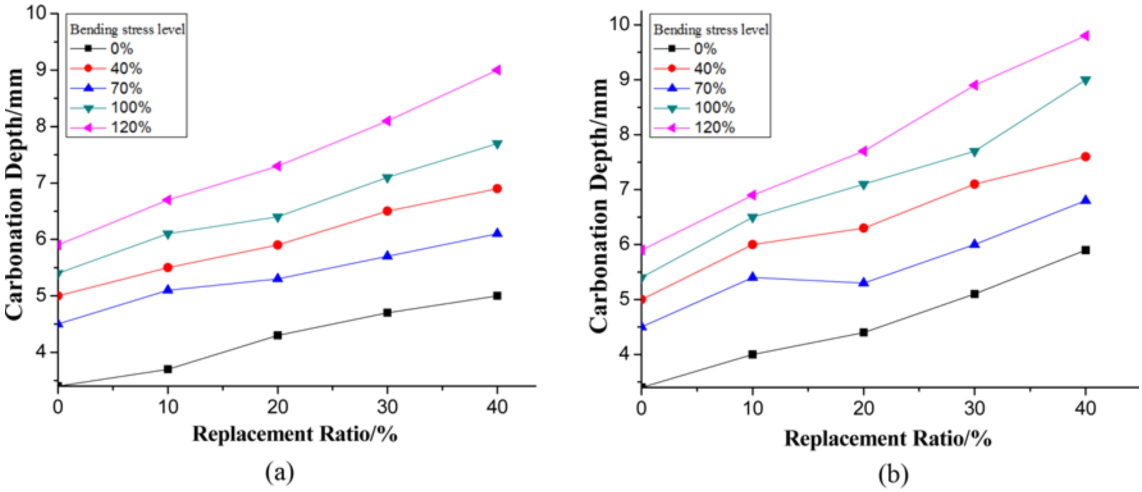


Fig. 1. 28 d Carbonation Depth with Increasing Replacement Ratio: (a) $RAC_1$, (b) $RAC_2$

thus the repeated RAC still had great workability. The slump value of NAC was 188 mm, higher than that of the two generations of RAC, and as the replacement ratio increased, the slump value of RAC tended to decrease. Meanwhile, the slump values of RAC decreased with increasing number of repetitions of the fine aggregates, and the sharpest decline was 6 mm. This decrease can be attributed to the increase in high-water-absorbing materials in recycled fine aggregates without water film formation on the surface, in contrast to NFA (Chen *et al.*, 2004). Moreover, with increasing number of repetitions, $RFA_2$ had more obvious disadvantages; the particles of the aggregates had a more angular, rough surface, with greater adherence of the old mortars, which decreased the workability of $RAC_2$.

In addition, the compressive strengths of NAC and two generations of RAC for ages of 28 days and 90 days are listed in the Table 4. The compressive strength of the NAC was 42.8 MPa and 49.6 MPa at the 28$^{th}$ and 90$^{th}$ days, what was the highest among the three types of concrete. Moreover, the compressive strengths of two generations of RAC at day 28, which all met the target compressive strength (30 MPa). This result shows that the repeated RFA concrete can meet the needs of the construction industry. The compressive strengths at the 90$^{th}$ day of $RAC_2$ decreased by approximately 3.3%, 3.7%, 6.1% and 8.9% compared with $RAC_1$, indicating that the performance degradation of $RFA_2$ was more serious than that of $RFA_1$. In addition, the compressive strengths of the two generations of RAC all exhibited a obvious drop as the replacement ratio increased; however, when the replacement ratio of RFA was 20%, the compressive strength of RAC exhibited only a slight drop compared with that at 10%. Similar results were reported by Xiao *et al.* (2011). The adherence of recycled fine aggregates to the cement particles would accelerate the hydration reaction and thus improve the compressive strength. However, the physical properties of the repeated recycled fine aggregates were inferior to that of the natural river sand, and there were some fine cracks of the RFA due to the accumulation of damage, which reduced the compressive strength of the RAC.

## 3.3 Carbonation Resistance

### 3.3.1 The Effect of Replacement Ratio

The carbonation depth change curves at the 28$^{th}$ day of $RAC_1$ and $RAC_2$ with different replacement ratios under different bending stress levels are shown in Figs. 1(a) and 1(b). The carbonation depths of NAC under the five bending stress levels were minima among the three types of concretes. For the RFA replacement ratio of 10%, the carbonation depths of $RAC_1$ under the five load levels had increased by 8.8%, 10%, 13.3%, 12.9%, and 13.6% compared with NAC, whereas the carbonation depths of $RAC_2$ increased by 8.1%, 9.1%, 5.9%, 6.6%, and 3.0% compared with $RAC_1$. This is because of the poor quality of RFAs, and the old cement mortar became more and more existed in the RFAs with the increase of cycling times. However, when the replacement ratio of RFA was 20%, the increase in carbonation depth slowed at low levels of bending stress, and a negative growth of the carbonation depth occurred at 70% of the failure load, with a decrease of 1.9% for $RAC_2$ compared with $RAC_1$. This behaviour may be explained by the old cement mortar in the RFA filled the micropores and limited the carbonation reaction, playing an active role in the resistance to carbonation under low levels of bending load. Meanwhile, when the replacement ratio of RFA was increased up to 40%, the carbonation depth increased sharply compared with NAC, and the carbonation depth of $RAC_2$ reached 9.8 mm, the maximum value among the three types of concrete. Several major factors account for the results, the porosity of RFA is greater than that of NFA, leading to RAC with higher porosity and lower density that facilitates invasion of the interior of the recycled concrete by $CO_2$. In addition, the old cement mortar adhered on the surface of the RFA offered abundant reactants for the carbonation reaction, thus accelerating the development of the carbonation process. Therefore the replacement ratio is an important factor of the carbonation behaviour of repeatedly RAC and the carbonation depth of $RAC_1$ and $RAC_2$ increased with increasing replacement ratio.

### 3.3.2 The Effect of Load Levels

The carbonation depths of $RAC_1$ and $RAC_2$ after 28 days under different load levels (40%, 70%, 100% and 120% of the failure load) were tested, and the results are shown in Fig. 2.

As shown in Fig. 2, the carbonation depth of $RAC_1$ suffering no load was 3.7 mm, 4.3 mm, 4.7 mm and 5 mm, indicating an increasing trend with increasing replacement ratio, and the carbonation speed of $RAC_2$ increased by 8.1%, 2.3%, 8.5% and 18%, respectively, compared with $RAC_1$. Furthermore, the carbonation depth of two generations of RAC increased with the increasing bending load except the load level was 70% of the failure load, the carbonation depth of $RAC_1$ had decreases of 7.3%, 8.5%, 12.3% and 11.6% compared with that under 40% of the failure load. At the same conditions, the carbonation depth of $RAC_2$ decreased sharply, with a maximum decrease of 15.8% when the replacement ratio of $RFA_2$ was 20%. This result illustrated that the bending load at 70% of the failure load had certain effect on delaying the carbonation process. Meanwhile, as the bending load increased to up to 120% of the failure load, the carbonation depths of $RAC_1$ and $RAC_2$ increased rapidly and reached maximum values of 9 mm and 9.8 mm. Thus, dual effects of bending load on the carbonation resistance were observed. When the bending load reached 70% of the failure load, a small amount of microcrack existed in the concrete, and the $CaCO_3$ produced by the process of carbonation filled the small fissures in the internal part of the concrete quickly, thus improving the carbonation resistance of the RAC. However, when the bending load increased to 120% of the failure load, the concrete began to crack, and the width of the crack inside the concrete increased greatly so that the carbonation products were unable to fill the crack with sufficient speed, thus accelerating the growth of cracks and improving the diffusion coefficient of $CO_2$ and the carbonation depth increased significantly.

### 3.4 Microstructure Analysis

Figure 3 shows microscopic views of NAC, $RAC_1$ and $RAC_2$ with a replacement ratio of 40% under a load level of 70% of failure load acquired by SEM. Concrete itself is a type of porous medium, and the internal pores increased during the preparation of $RAC_2$. In addition, the microstructural features of the interfacial transition zone between aggregates and cement paste are associated with the degree of density of the aggregate (Dong *et al.*, 2009; Shui *et al.*, 2003).

As shown in Fig. 3, the internal structure of NAC was compact

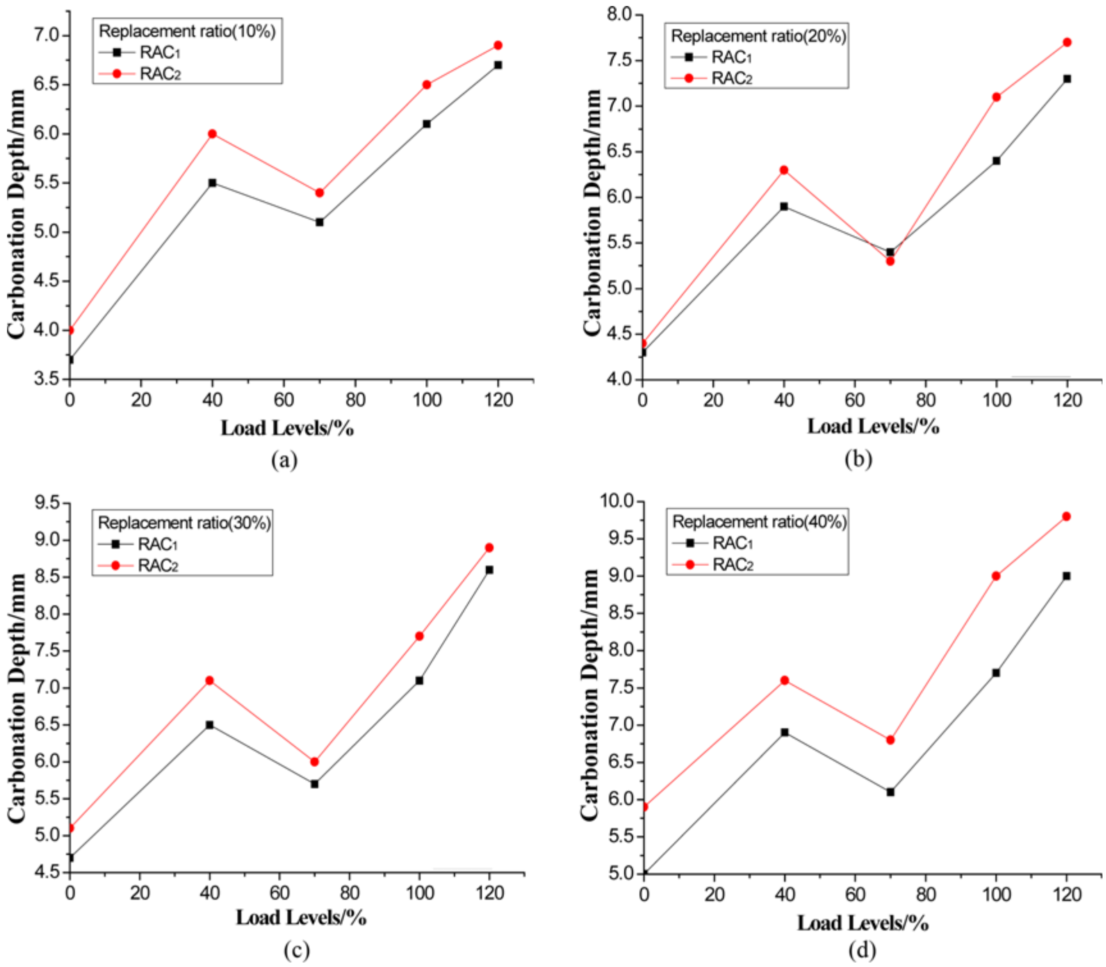


Fig. 2. Carbonation Depth of RAC under Different Load Levels: (a) 10%, (b) 20%, (c) 30%, (d) 40%

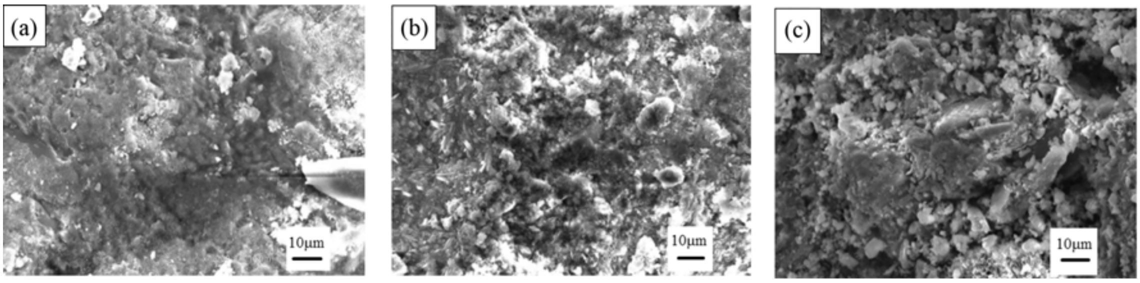


Fig. 3. Micromorphology of: (a)NAC, (b) $RAC_1$, (c) $RAC_2$

Table 5. Minimum Thickness *c* (mm) of Protection Layer for Steel Bar of Concrete Beam

| Environmental action grade | Structure design service lifetime | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 100 years | | | 50 years | | | 30 years | | |
| | Strength grade | Maximum water-binder ratio | c | Strength grade | Maximum water-binder ratio | c | Strength grade | Maximum water-binder ratio | c |
| I-A | C30<br>≥ C35 | 0.55<br>0.5 | 25<br>20 | C25<br>≥ C30 | 0.60<br>0.55 | 25<br>20 | ≥ C25 | 0.60 | 20 |
| I-B | C35<br>≥ C40 | 0.50<br>0.45 | 35<br>30 | C30<br>≥ C35 | 0.55<br>0.50 | 3025 | C25<br>≥ C30 | 0.60<br>0.55 | 3025 |
| I-C | C40<br>C45<br>≥ C50 | 0.45<br>0.4<br>0.36 | 45<br>40<br>35 | C35<br>C40<br>≥ C45 | 0.50<br>0.45<br>0.40 | 4035<br>30 | C30<br>C35<br>≥ C50 | 0.55<br>0.50<br>0.45 | 35<br>30<br>25 |

Note: I-A,I-B and I-C represent the degrees of dry-wet alternate action as slowly, moderately and rapidly.

and homogeneous, with few micropores in the concrete. However, micropores began to appear in $RAC_1$, and a few small micro cracks were observed inside the concrete under the 70% damage load. In addition, a large number of cracks occurred in $RAC_2$, and more crystals of $CaCO_3$ and $SiO_2$ produced by carbonation were observed, with abundant old cement mortar in the concrete interface. Reasons for these observation include a decrease in fine aggregate quality with increasing number of iterations, which led to a loose internal structure of the repeated RAC, with a gradual increase in porosity. Furthermore, the development of internal micro cracks was promoted under the bending load, which reduced the compactness of the RAC. Therefore, with increasing number of iterations, the strength and durability of repeated RAC declined because of the decrease in the quality of the RFA, consistent with the results of Li *et al*. (2005).

### 3.5 Engineering Verification of the Repeated RAC

Based on Fick's first law of diffusion, the existing carbonation predicted models of NAC are multiplied by one or more coefficients on the basis of the relationship between carbonation depth and time. However, studies of carbonation prediction models of repeatedly RAC are scant in China and abroad. Xiao *et al*. (2008) put forward the carbonation depth prediction model of RAC, and this model is proved effectively to predict the carbonation depth of RAC at loading conditions, and the coefficient correlation is up to more than 0.97. This study simulated the carbonation process of concrete beam at loading environment to evaluate the feasibility of the repeated use of RFA in structural concrete. For this purpose, the carbonation depth prediction model was used as follows:

$$X_C = K_{CO_2} K_{k1} K_{kS} T^{0.25} R^{1.5} (1-R)\cdot\left(\frac{230}{f_{cu}^{RC}} + 2.5\right)\sqrt{t} \quad (1)$$

where the several parameters, the $CO_2$ concentration $K_{CO_2}$, position influence coefficient $K_{k1}$, stress type coefficient $K_{kS}$, temperature *T*, relative humidity *R* and RAC compressive strength $f_{cu}^{RC}$, are considered.

The service environment of structural concrete can be classed into five categories in terms of GB/T 50476-2008 (2008) and in general environment (Category I), carbonation is a dominant factor affecting the durability of concrete structures. In order to meet the carbonation durability of concrete engineering, Table 5 gives the Minimum thickness of protection layer for steel bar of concrete beam in general environment.

The environmental conditions of practical engineering meet the Category I environment in southern China. With Guangzhou for a case study, where the concentration of $CO_2$ is 0.04%, the annual average temperature and relative humidity are 21.7ºC and 82%. As shown in Eq. (1), the carbonation depth of NAC and two generations of recycled fine aggregate concrete ($RAC_1$ and $RAC_2$) after 50 years service can be calculated. Thus, the carbonation depth of NAC is 22.5 mm, and the carbonation depth of $RAC_1$ and $RAC_2$ reach the maximum, which are 26.0 mm and 26.8 mm, when the replacement ratio is 40%. Meanwhile, the carbonation depth of NAC, $RAC_1$ and $RAC_2$ are all less than 30 mm, which clearly reveals that all of the concrete beams prepared by repeated RAC have satisfactory carbonation resistance, according to the requirements for a design service lifetime of 50 years at the environmental action of I-B grade, as shown in Table 5. Therefore, the carbonation resistance of repeated RAC can meet the requirements for a design service lifetime of 50 years under bending load environment. Finally, it can be concluded that the use of two generations of repeated RAC with proper replacement (10%, 20%, 30% and 40%) into practical engineering is feasible.

## 4. Conclusions

In this work, the properties and the carbonation resistance of repeated RAC prepared with $RFA_1$ and $RFA_2$ to replace NFA were studied. Based on the results and discussion, the following conclusions can be drawn:

1. The quality of the fine aggregates declines with increasing number of repetitions. Compared to natural fine aggregate, $RFA_1$ and $RFA_2$ has 8.9% and 10.9% lower apparent density and 11.9% and 12.8% higher water absorption.
2. The slump values and compressive strengths of RAC decreases with increasing replacement ratios and number of repetitions, and meet the target slump and compressive strengths.
3. The carbonation depth of RAC increases with increasing replacement ratio of RFA, and the carbonation depth of $RAC_2$ is greater than that of $RAC_1$. When the replacement ratio of RFA was 20%, the growth of the carbonation depth slowed and even became negative.
4. The carbonation depth of $RAC_1$ and $RAC_2$ increases with increasing load level except 70% of the failure load, where the carbonation depth of $RAC_2$ decreased sharply, with a maximum decrease of 15.8% when the replacement ratio of $RFA_2$ was 20%.
5. Scanning electron microscope pictures reveal differences in micro pores and micro cracks of NAC and the repeated RAC under the same load levels, indicating that the carbonation resistance of RAC would deteriorate steadily with increasing number of repetitions.
6. The carbonation resistance of repeated RAC can meet the requirements for a design service lifetime of 50 years under bending load environment, so the repeated RAC made with RFA with replacement level of 10%, 20%, 30% and 40% could be used in practical engineering .

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